Feasibility of atlas-based segmentation of the brain in the presence of tumor by a weighted least-squares demons algorithm

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Introduction MR-images of the brain can be segmented by registration with an atlas. A common way to do so is to first register the brain volume with an intensity atlas and consequently to propagate the labels of the atlas to the target brain volume according to the resulting deformation field. However, most intensity-based registration algorithms fail in the presence of pathologies, like brain tumors or MS lesions. The demons algorithm, as introduced by Thirion et al.[1], starts from a constant brightness assumption, which means that intensities of corresponding voxels in the atlas and target image are assumed to be identical. In the presence of brain tumor, the intensities are altered and the constant brightness assumption is locally violated. As is pointed out by Li et al.[2], this causes false deformations of the atlas and leads to gross segmentation errors in the vicinity of the tumor. We study the possibility to improve the robustness of the demons algorithm in the presence of pathology by minor, easy-to-implement, modifications of the demons force.

Method In the demons algorithm, the similarity measure and regularization term are accommodated for in two different cost functions, which are solved for iteratively. The demons force is the explicit expression of a minimization step of the similarity measure and provides a (non-smooth) update of the displacement field. After each update of the displacement field, the resulting field is smoothed and a new force field can be calculated. As long as the constant brightness assumption is valid, the method converges towards a smooth alignment of both images. Following the notation of Vercauteren et al.[3], the demons force equals

$$\mathbf{u}(p) = -\frac{F(p) - M\circ s(p)}{\left|\left|\nabla F_p^T\right|\right|^2 + \frac{\sigma_i^2(p)}{\sigma_x^2}} \nabla F_p^T$$

with $\mathbf{u}(p)$ the force vector in each voxel, $F(p)$ and $M\circ s(p)$ the fixed and moving image, ∇F_p^T the gradient of the fixed image, and σ_i and σ_x are parameters characterizing the image noise and the transformation uncertainty respectively. As the demons force relies on the method of least squares regression, the algorithm minimizes the squares of the intensity residues. However, least-squares estimators are sensitive to outliers in the data. In practice, this means that the demons algorithm gives rise to large, undesirable forces on locations where the constant brightness assumption is violated, such as locations of tumors. To reduce the effect of those outliers, it is advantageous to use a regression technique that is more robust to the presence of outliers. M-estimators try to reduce the influence of outliers by replacing the squared residuals with another function of the residuals, preferably a function with a low value for residuals that are abnormally large. Implementation-wise, the use of M-estimators coincides with an iterative weighted least-squares approach. Although the possibilities for the choice of weighting functions are plenty, we restrict ourselves here to the use of the $L_1 - L_2$ M-estimator[4]. The modified demons force equals

$$\mathbf{u}(p) = -\frac{w_p[F(p) - M\circ s(p)]}{w_p\left|\left|\nabla F_p^T\right|\right|^2 + \frac{\sigma_i^2(p)}{\sigma_x^2}} \nabla F_p^T$$

with $w_p = 1/\sqrt{1 + x^2/2}$ is the weighting function of the intensity residues. As a qualitative validation of this modified algorithm, we compare the segmentation result obtained by both the conventional and modified demons algorithm with the ground truth segmentation around a tumor area[5]. For the experimental setup, a healthy brain volume is used from the BrainWeb database[6] (subject04). The algorithm of Prastawa et al.[7] allows us to simulate a tumor in this reference image [Fig 1a] and results into a ground truth segmentation of the brain tissues after tumor insertion [Fig 1b]. This ground truth segmentation is visually compared with an atlas-based segmentation obtained by the conventional demons registration [Fig 1c] and the weighted least-squares demons registration [Fig. 1d].

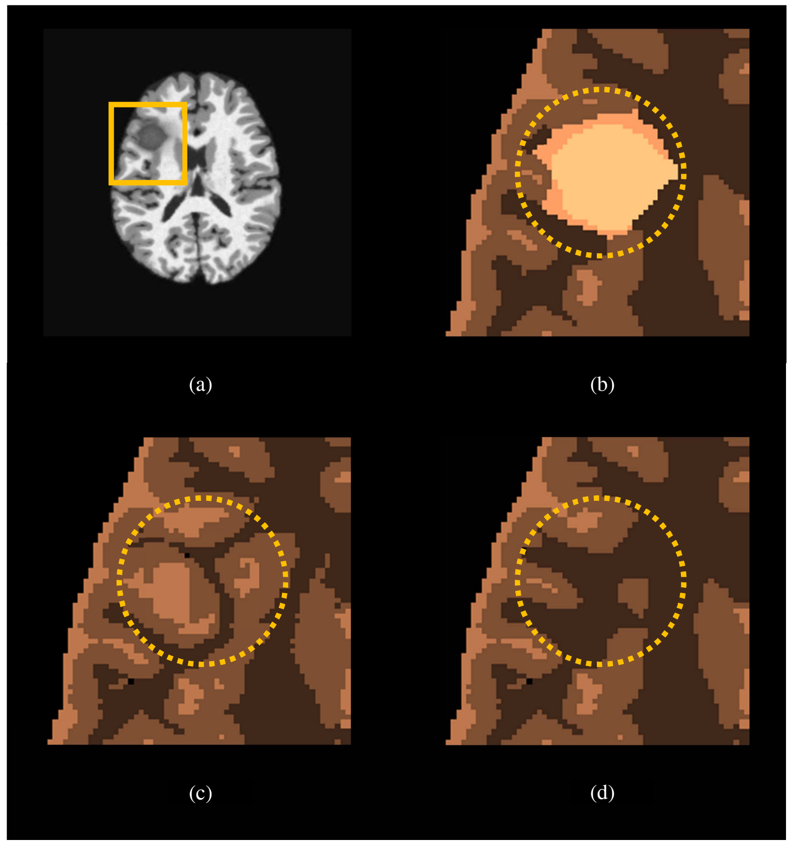

Fig 1: (a) Brain volume with tumor, (b) ground truth segmentation, (c) segmentation by the conventional demons algorithm and (d) segmentation as obtained by the weighted least-squares demons algorithm. The orange circle provides a reference for the location of the tumor.

Results and Discussion In the vicinity of the tumor, there is an obvious bias between the segmentation obtained by the conventional demons algorithm and the ground truth segmentation. The ground truth is much better estimated by the weighted least squares demons algorithm. Although this work is merely preliminary and the validation is only qualitative, it appears possible to largely improve the robustness of the demons algorithm for atlas-based segmentation in the presence of pathology by minor and easy-to-implement modifications of the demons force.

References [1] Thirion J. Image Matching as a Diffusion Process: an Analogy with Maxwell's Demons. *Medical Image Analysis*. 1998;2:243-260 [2] X. Li et al. Registration of Images with Varying Topology using Embedded Maps. *IEEE TMI*. 2012:31(3) [3] Vercauteren T. et al. Diffeomorphic Demons: Efficient non-parametric Image Registration. *NeuroImage*. 2009;45(1): 61-72 [4] Zhang Z. Parameter Estimation Techniques: A Tutorial with Application to Conic Fitting. *Image and Vision Computing*. 1997;15(1) [5] Lamecker H. et al. Atlas to Image-with-Tumor Registration based on Demons and Deformation Inpainting. *MICCAI Workshop CIBT*. 2010. [6] Cocosco C.A. BrainWeb: Online Interface to a 3D MRI Simulated Brain Database. *NeuroImage*. 1997;5(4) [7] Prastawa M. et al., Simulation of Brain Tumors in MR Images for Evaluation of Segmentation Efficacy. *IEEE TMI*. 2009;13(2): 297-311